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Experiments with New Electric Devices for Pasteurizing Soils

A. G. Newhall

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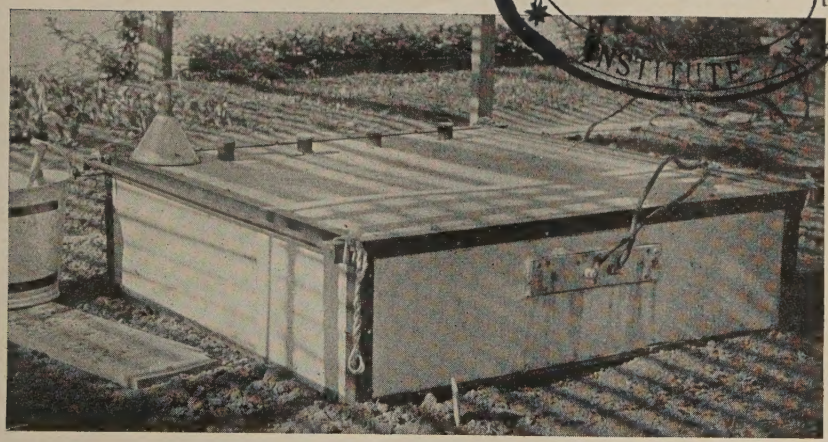

AN ELECTRICALLY OPERATED INVERTED STEAM PAN FOR GREENHOUSE OR OUTSIDE USE

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P.A.B

EXPERIMENTS WITH NEW ELECTRIC DEVICES FOR PASTEURIZING SOILS[1]

A. G. Newhall

The many advantages of heat as an agent for disinfesting soils, particularly soils that have become unproductive from the accumulation of parasitic fungi, nematodes, weed seeds, and insect pests, have long been recognized. Heat is quick and transient, but is very thorough. It destroys all pests. Many growers of flowers and vegetables who do not have equipment to steam-"sterilize" are finding that limited quantities of soil can be economically and satisfactorily "pasteurized" with some sort of electrical device.

METHODS OF SOIL-PASTEURIZING

DIRECT-HEATING METHOD

Two general methods involving the use of different kinds of electrical equipment have been developed. In one, the direct-heating method, the soil-resistance principle is employed in which the current passes directly through the soil from one metal plate, or electrode, to another. Charles W. Wildebour appears to have been the first to employ the method in America (Anonymous, 1932). He and Glen Cushing worked in cooperation with C. F. Doucette, then in charge of the entomological laboratory of the United States Department of Agriculture at Sumner, Washington. They heated 20 square feet of bench soil at a time, from 60° to 180° F. in about two hours, with 70 kilowatt-hours on 230-volt alternating current. A year later, Fee (1933) described the successful use of vertical plates in a greenhouse bench where 15 square feet was treated at a time on a 30-ampere 230-volt alternating-current line. Similar results were obtained in the same year by Krewatch and Kable (1933), who made a comprehensive report on the procedure and pointed out a number of the limitations and difficulties involved in applying this method to the treatment of bench soil and ground beds.

A box type of pasteurizer also was developed in the Washington experiments described by Scott (1932). This was capable of raising the temperature of about ¾ cubic foot of soil to 180° F. in 4½ minutes by employing vertical metal blades (electrodes) 2 inches apart in a box 12 by 18½ inches in size and 5½ inches deep. Blauser (1934?, 1935) improved on the construction of this cabinet type by employing but two horizontal electrodes 10 inches apart, in place of numerous vertical ones. He was able to obtain satisfactory temperatures with the expenditure of less than 1 kilowatt-hour per cubic foot of soil. He stated that resistance to the current was directly proportional to the distance apart of the electrodes and inversely proportional to their area. As a standard size for a pasteurizer to be used on 230-volt alternating current and where a maximum service of 50 amperes was available, he settled on one 24 by 36 inches in size and 10 inches deep; but he stated that if a maximum of only 25 amperes was available, the dimensions should be cut to 24 by 18 by 10 inches. If the depth was reduced to 5 inches, the demand would then be equal to that of the

[1]This is one of several agricultural-research projects undertaken with funds supplied by the Empire State Gas & Electric Association.

larger pasteurizer while the volume would be cut to one-fourth; and hence the time required to reach the end point, and the total current consumed, would also be but one-fourth of those with the larger box. The work of Tavernetti (1935) confirmed the results obtained by others.

Newhall and Nixon (1935) made a study of the direct-heating (Ohio) type of cabinet pasteurizer (figure 1), and found that the current consumed per cubic foot of soil per degree rise in temperature ranged from 22 watts for sand to 28 watts for muck with its higher water content. Greater efficiency than this has recently been obtained by Cruz (1939), who employed a constant-current transformer which automatically stepped up the voltage whenever the charge of soil had a relatively high resistance (as sand) and reduced the voltage when a soil with high conductivity (as muck or compost) was being heated. In general, the experiments in America clearly indicate that a cubic foot of soil can be heated sufficiently to kill pathogenic microorganisms and weed seeds with about 1 kilowatt-hour of electricity when 230 volts are used, and with even less if higher voltages can be employed.

In Europe, similar experiments have been conducted with direct-heating equipment along parallel lines with those in America. Dix and Rauterberg

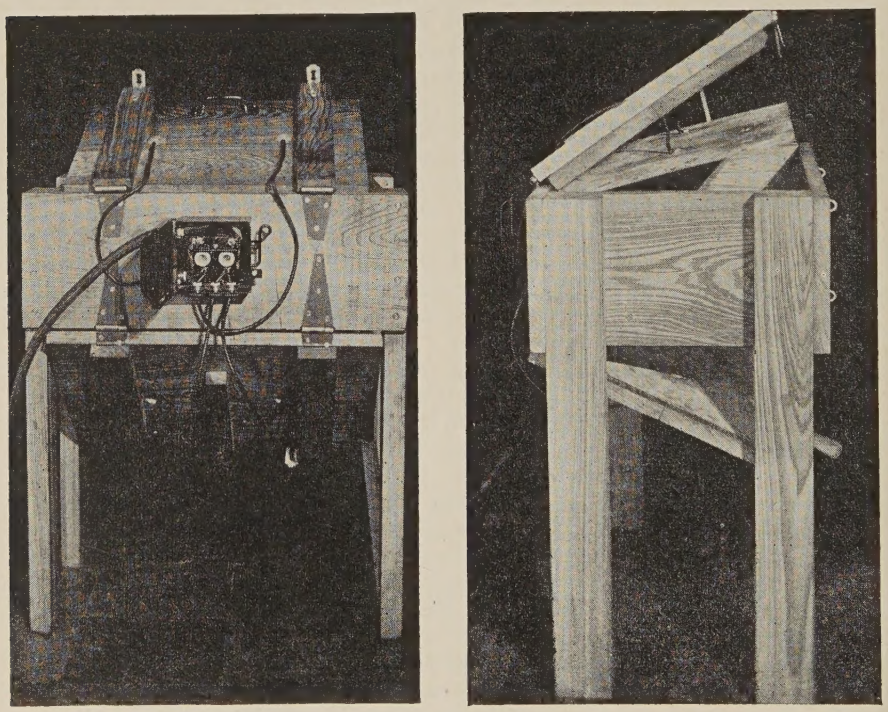


FIGURE 1. A DIRECT-HEATING SOIL PASTEURIZER, OHIO TYPE, WITH A CAPACITY OF 2.4 CUBIC FEET

The current passes directly through soil from one horizontal electrode to another. On 230-volt alternating current, it takes from 25 minutes to 6 hours to treat a charge of soil. The current demand is variable, and exceeds 5 kilowatts under some soil conditions

(1933), in Germany, used a three-phase circuit and a transformer with a capacity of 3.6 to 60 amperes at voltages between 2750 and 200. Seven parallel vertical electrodes were placed in the soil at intervals varying between 8 and 78 inches in different experiments. The best results were said to have been obtained when electrodes were approximately 20 inches apart and a 500-volt current was employed. By using strong currents for relatively short periods of time, greater economy was obtained. Thus a cubic yard of soil could be brought up to 70° or 80° C[2] with 9 to 16 kilowatt-hours, or less than ½ kilowatt-hour per cubic foot.

Both the American and the European experiments have shown that success with the vertical-plate method of direct heating requires a transformer, which is costly, that certain hazards to life and loss of current are hard to avoid, and that unless considerable labor and careful attention to details are employed uniform results cannot be expected. As a consequence, the vertical-plate direct-heating method has not found favor with practical growers.

Experiments with horizontal electrodes in a cabinet-type pasteurizer were conducted in Holland by Kroft and Groen (1933). Muyzenberg and Rijn (1937) then studied the device more thoroughly with respect to the effect of electrolytes, moisture, and compression on the conductivity of sand and soil. Their figures for current consumption were high—from 1.6 to 4+ kilowatt-hours per cubic foot—but their final temperatures were also rather high (99° C.).

Certain objectionable features of the direct-heating method include hazards to the operator, the variable and often very high demand made on the service line, and the care required in loading the chamber with soil to get uniformity in packing, in moisture content, and in contact between soil and electrodes, not to mention the frequent necessity of adding some dilute electolyte solution (sodium or potassium nitrate or sulfate) to increase the conductivity of sand. Taken all together, these are believed by many to outweigh the advantages of economy of construction and speed of operation pertaining to the direct-heating type of cabinet.

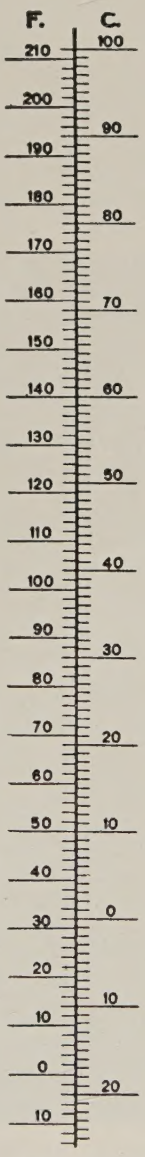


FIGURE 2. FAHRENHEIT-CENTIGRADE CONVERSION SCALE

INDIRECT-HEATING METHOD

The other general method of soil-heating employs the heating-element principle in which the current passes through covered, resistance, heating units properly spaced to impart their heat to the soil by

[2]A centigrade-Fahrenheit temperature-conversion scale is shown in figure 2.

thermal conductance. Cabinet pasteurizers operating on this principle, first described by Carney (1932) and further tested by Horsfall (1935) and by Newhall and Nixon (1935), have become known as the New York type (figures 3 and 4).

Newhall and Nixon found this kind of pasteurizer capable of heating soils to satisfactory temperatures (70° C.) with the expenditure of electric energy varying between 1.0 and 1.3 kilowatt-hours per cubic foot of soil treated, depending on the kind of soil, the initial temperature, and the moisture content. They concluded that the sum total of the advantages and disadvantages of the two general methods of pasteurizing was in favor of the indirect, because of its greater safety and simpler operation. They built cabinets holding up to 3 or 4 cubic feet of soil for $20 to $30, and

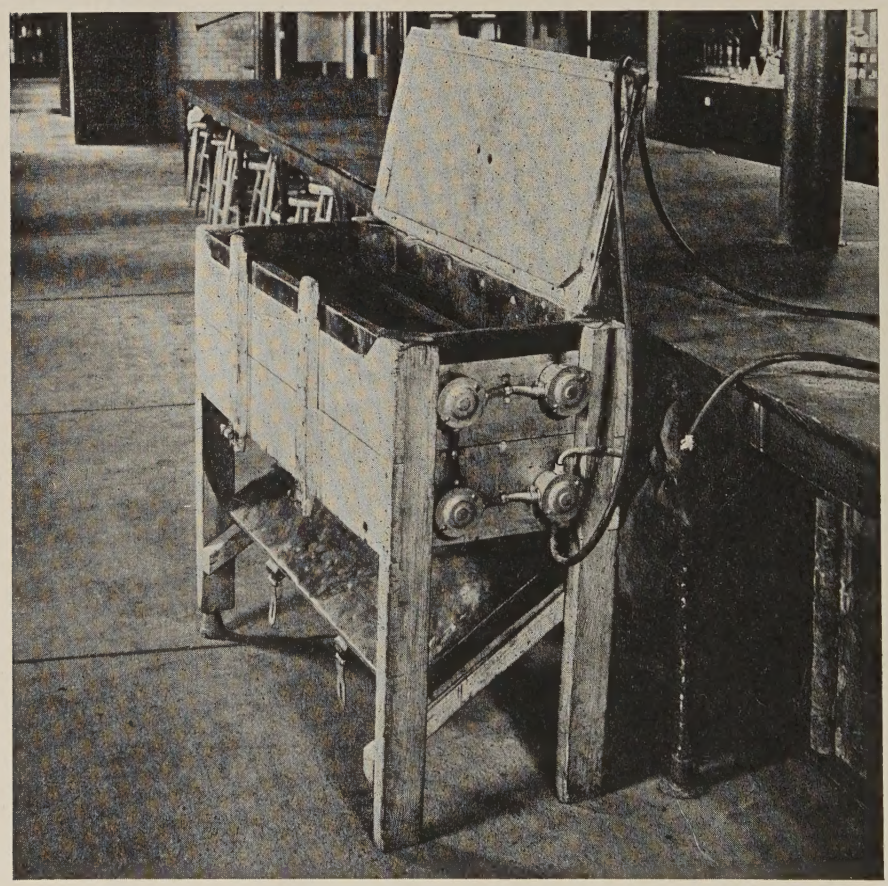


FIGURE 3. AN INDIRECT-HEATING SOIL PASTEURIZER, NEW YORK TYPE, WITH A CAPACITY OF 5 CUBIC FEET

This may be used on either 115- or 230-volt alternating current. Pipe-type space heaters with a constant-current demand of 1600 watts, are employed. It takes 4 to 5 hours to treat a charge of soil. The pasteurizer is lined with copper and insulated with composition board and has been in use for over four years without repair

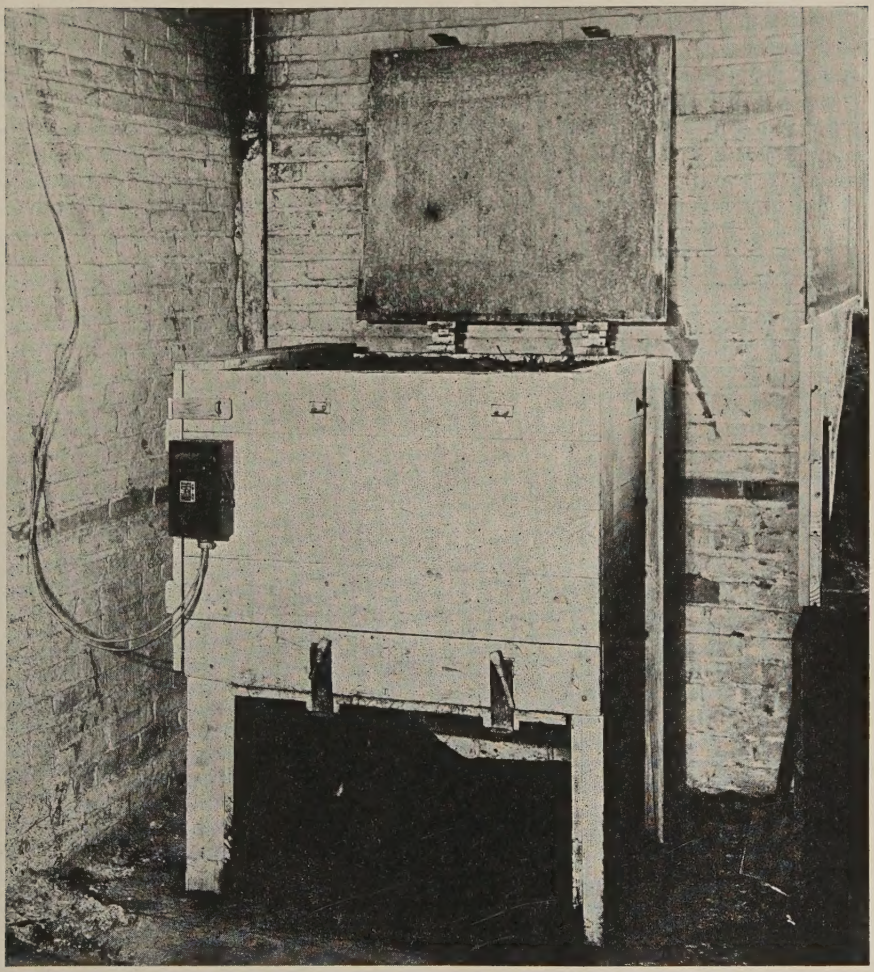


FIGURE 4. A POPULAR, SERVICEABLE, INDIRECT-HEATING SOIL PASTEURIZER, NEW YORK TYPE, WITH A CAPACITY OF ½ CUBIC YARD

This is equipped with "Calrod" heaters rating 3000 watts, and may be used on either 115- or 230-volt alternating current

assembled one holding ½ cubic yard for $67. Since 1931, when these were originally designed, there have probably been more than 100 such pasteurizers, of different sizes, purchased or built by growers in New York and neighboring States[3]. The largest are believed to hold 1 cubic yard, while the most popular seems to be the ½-cubic-yard size which operates on either 115 or 230 volts and has a connected load of 3000 watts, or 222 watts per cubic foot.[4]

[3]From information supplied by manufacturers.

[4]Since these experiments were completed, a handy-sized portable electric pasteurizer holding 2 bushels of soil has been placed on the market. It is shaped like a large suitcase, contains one 750-watt Calrod heater, and has been giving satisfactory service in the Department of Entomology and Limnology at Cornell University. This pasteurizer is illustrated in figure 9.

The matter of the wattage required and the proper spacing of the heaters was studied by Newhall and Nixon. They found that a considerable leeway is permissible in this respect. With pipe-type heaters of ¾-inch galvanized iron, which can be obtained in almost any desired length and wattage rating,[5] good results were obtained when the heat flux per square inch of heater surface varied between 2.12 and 2.45 watts. Heaters should be so rated and so spaced as to deliver from 200 to 300 watts per cubic foot of soil, and no portion of the soil should be more than 8 inches from a heater.

THERMAL DEATH-POINTS OF PATHOGENIC MICROORGANISMS

In a former publication the author gave evidence that in the presence of ordinary soil moistures a final temperature of 70° C. is high enough to kill a variety of pathogenic microorganisms, including members of such genera as Rhizoctonia, Sclerotinia, Phytophthora, Fusarium, Heterodera, and Erwinia, in less than an hour (Newhall and Nixon, 1935). Blauser (1935) concluded that 60° C. is high enough to kill nematodes (Heterodera) and most weed seeds, but that 65° is required to kill the Fusarium causing tomato wilt. Horsfall (1935) has noted the efficacy of long-time low-temperature treatment for damping-off control, 45° to 55° C. having been found high enough in some cases where an overnight treatment was made.

To test the supposition that 60° C. is a sufficiently high end temperature for damping-off control, a number of flats of soil known to possess damping-off organisms were heated in a Nixon dairy-utensil sterilizer (described later) until the following temperatures were reached: 40°, 45°, 50°, 55°, 60°, and 95° C. Each flat was subsequently sown with vegetable seeds, and records of damping-off were kept. The results indicated that heating

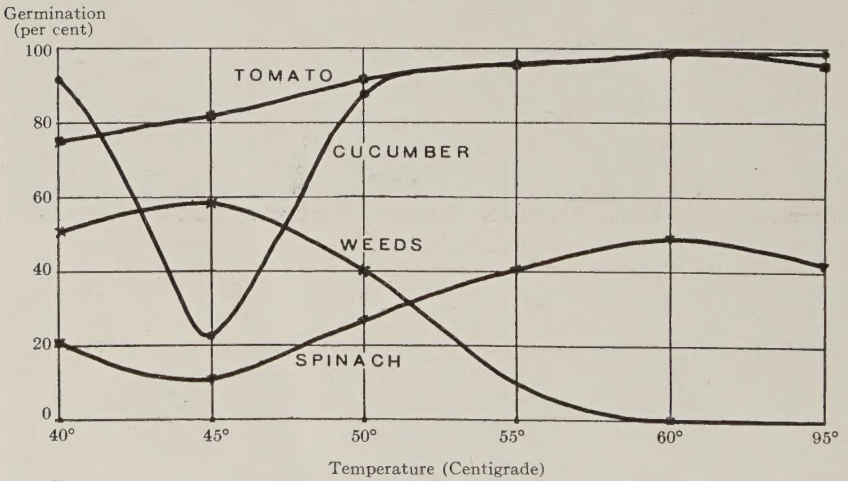


FIGURE 5. EFFECT OF HEATING LOAM SOIL TO CERTAIN FINAL TEMPERATURES, ON DAMPING OFF OF SOME VEGETABLE SEEDS AND ON GERMINATION OF WEED SEEDS

The germination in untreated soil was as follows: spinach, 13 per cent; tomato, 77 per cent; cucumber, 95 per cent; weeds, 45 per flat

[5]Hynes & Cox Electric Corporation, Albany, New York.

to 60° was as effective as was heating to 95°. Perhaps the time factor is of importance here, as it took three hours to attain the maximum temperature (figure 12, page 21). Most of the weed seeds were apparently destroyed when the temperature stopped at 60°, although the legumes and Capsella were exceptions and probably there are other exceptions. Weeds found in the checks included Amaranthus, Anthemis, Barbarea, Capsella, Cerastium, Lamium, Oxalis, and Stellaria.[6] The data from these tests are summarized graphically in figure 5. A point of some interest is the apparent increase in damping-off of spinach and cucumber, and in the germination of weed seeds, by heating the soil to only 45°. Such treatment rendered conditions worse than in the checks, although there have not been a sufficient number of trials to warrant assuming this to be generally true. Substantiation of the idea that a final maximum temperature of 60° is sufficient for damping-off control is presented in figure 6, in which stands of cucumbers, tomatoes, and spinach are shown in soil heated to three temperatures as compared with an unheated check.

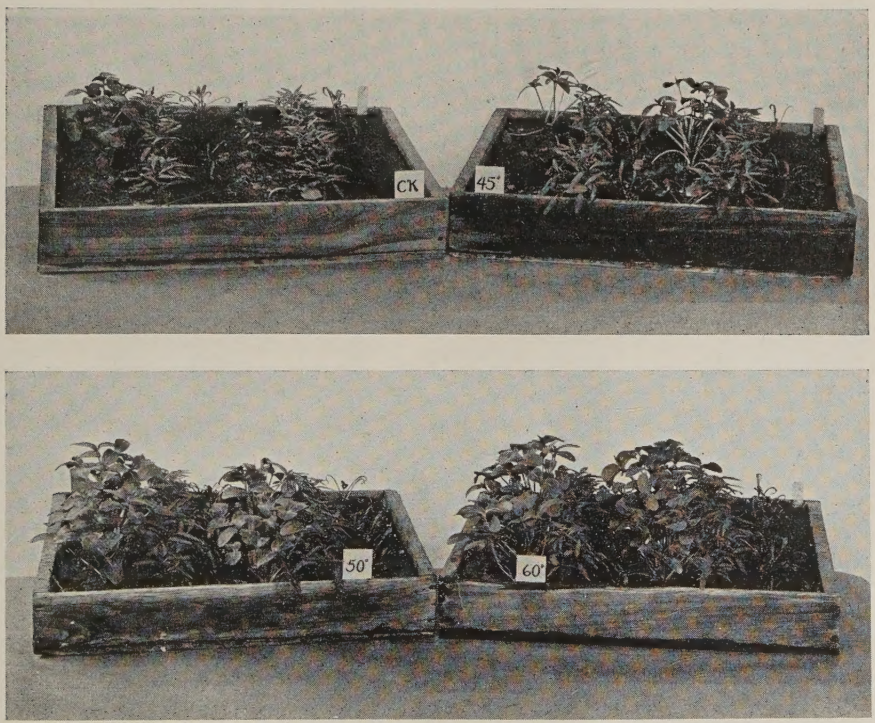


FIGURE 6. STANDS OF REPLICATE PLANTINGS OF CUCUMBERS, TOMATOES, AND SPINACH, IN SOILS HEATED TO THE FINAL MAXIMUM TEMPERATURES INDICATED (45°, 50°, AND 60° C.) IN THE NIXON DAIRY PASTEURIZER

No damping-off occurred in the soil heated to 60° C., though some was present in the samples brought to 50° and 55° C.

[6]Identification of weeds was done by Professor W. C. Muenscher, of the Department of Botany at Cornell University.

Further confirmation of this important generalization, that effective soil treatment requires heating only to 60° C., is presented in the form of a table of thermal death-points of a number of microorganisms, other than bacteria, of variable pathogenicity (table 1). Examination of these data show that few fungi can withstand 65° C. even for 10 minutes. Sclerotia are no exception. Some of the molds which may be wet with difficulty are more resistant. Turning for a moment to bacteria, Elliott (1930) gives data on the thermal death-points of 102 bacterial plant pathogens, of which only 4 lie above 59° and none is above 69°.

TABLE 1. THERMAL DEATH-POINTS OF A NUMBER OF MICROORGANISMS OF VARIABLE PATHOGENICITY

Pathogen	Form	Temperature (C.)	Time (minutes)	Authority
Actinomyces scabies	Conidia	54°	10	Lutman and Cunningham (1914)
Alternaria solani	Conidia	45°	—	Rands (1917)
*Aspergillus niger**	Spores	55°	30	Wallace and Tanner (1931)
Botrytis cinerea	Mycelium and spores	55°	15	Zumstein (1936)
Botrytis cinerea	Conidia	50°	10	Smith (1923)
Cercospora apii	Mycelium and spores	52°	10	Klotz (1923)
Cladosporium fulvum	Spores	70°	1	Bewley and Buddin (1921)
Colletotrichum lindemuthianum	Mycelium	50°–52°	10	Muncie (1917)
	Spores	46°–48°	10	Muncie (1917)
C. oligochaetum	Spores	60°	1	Bewley and Buddin (1921)
C. lini	.....	50°	30	Vladimirskaya (1930)
Diaporthe batatatis	Conidia	48°–49°	10	Harter and Field (1913)
Ditylenchus dipsaci	Larvae	43.5°	46	Ramsbottom (1918)
D. dipsaci	Larvae	48.5°	15	Ramsbottom (1918)
D. dipsaci	Larvae	52.5°	11	Ramsbottom (1918)
D. dipsaci	Larvae	57.5°	5	Ramsbottom (1918)
Fusarium eumartii	Mycelium and spores	55°	15	Zumstein (1936)
F. lycopersici	Mycelium and spores	65°	10	Zumstein (1936)
F. moniliforme	Conidia	70°	10	Merrill (acc. Hartley, 1921:28)
F. oxysporum	Mycelium	58°–59°	5	Wood (1939)
Helminthosporium salivum	Mycelium and spores	54°	10	Christensen (1926)
Heterodera marioni	All stages	48°	10	Newhall (1930)
Macrosporium solani	Mycelium and spores	50°	5	Zumstein (1936)
Marssonina panattoniana	Conidia	40°	10	Brandes (1918)
Mucor species†	Conidia	57°	30	Thom and Ayers (1916)
Oidium lactis‡*	Spores	60°	30	Wallace and Tanner (1931)
Penicillium species§	Conidia	60°	30	Thom and Ayers (1916)
Phoma apiicola	Spores	49°	10	Bennett (1921)
Phytophthora citrophthora	Mycelium and zoospores	43.3°	5	Klotz (1940)
P. parasitica	Mycelium and spores	60°	1	Bewley and Buddin (1921)
P. cryptogea	Mycelium	50°	1	Bewley and Buddin (1921)
Plasmodiophora brassicae	.....	60°	30	Vladimirskaya (1930)
Pythium debaryanum	Mycelium	40°	10	Zumstein (1936)
P. debaryanum	Mycelium and spores	65°	10	Merrill (acc. Hartley, 1921:28)
Rhizoctonia (=*Corticium centrifugum*)	Sclerotia in water	50°	50	Watanabe (1933)
C. centrifugum	Sclerotia in air	50°	60	Watanabe (1933)
C. centrifugum	Mycelium in water	45°	30	Watanabe (1933)
C. centrifugum	Mycelium in air	45°	20	Watanabe (1933)
Rhizoctonia crocorum	Mycelium	45°–48°	60	Newton (1931)
R. solani	Mycelium	45°–60°	60	Newton (1931)
R. solani	Sclerotia	55°–60°	60	Newton (1931)
Rhizopus nigricans	Spores	54.5°	30	Thom and Ayers (1916)
*R. nigricans**	Spores	50°	20	Wallace and Tanner (1931)
Sclerotinia sclerotiorum	Sclerotia	48°–50°	5	Joshi (1924)
S. delphinii	Sclerotia	50°	10	Zumstein (1936)
S. rolfsii	Sclerotia	50°	10	Zumstein (1936)
Septoria lycopersici	Spores	52°	10	Levin (1916)
S. apii	Mycelium	44°	10	Cochran (1932)
S. apii-graveolentis	Mycelium	42°	10	Cochran (1932)

*Suspended spores in dilute salt solution. Longer time sometimes needed in sugar solutions.
†Four species with thermal death-point below 57° C.
‡Survived 60° C. for 30 minutes. No survival at 62.8° according to Thom and Ayers (1916).
§Twenty-three species with thermal death-point below 60° C.

Valleau, Karraker, and Johnson (1926) found that heating soil to 65° C. for 15 minutes was sufficient to kill a Fusarium and a "Pythiumlike" organism causing root-rot of corn.

In studying the diseases of mushrooms, several workers recently have made pertinent observations on time-temperature conditions lethal to certain pathogens attacking this crop. Lambert (1930) found mycelium and chlamydospores of *Mycogone perniciosa*, the cause of "bubbles", to be killed in one hour at 50° C. and in six hours at 42° C.; artificially infested soil was rendered safe after a six-hour treatment at 45° C. Ware (1933) found that *Verticillium Malthousei* (brown spot) was killed in six hours at 40° C. Beach (1937) found that the following organisms did not survive soil temperatures fluctuating between 115° and 120° F. (46° and 49° C.) if such temperatures were maintained for sixteen to twenty-four hours: *Bacterium* sp. (brown blotch), *Cephalothecium* sp. (casing mold), *Dactylium* sp. (mildew), *Monilia fimicola* (white plaster mold), *Mycogone perniciosa* (bubbles), *Trichoderma koningi* (green mold), and *Verticillium* sp. (brown spot); spores of certain species of Penicillium and Aspergillus, however, survived six-hour exposures in a water bath at 140° F. (60° C.). Lambert (1932) reports that the spores of *Pseudobalsamia microspora* (truffle) survived 82° C. for five hours, and Beach found them to survive a 2-day heating in compost at 57° C. Beach concludes that 120° F. (49° C.) is sufficient to kill the more important harmful fungi in mushroom beds during the rather long period of heating attending the composting process, while 130° F. (54° C.) is preferable where insects must be driven out. This latter temperature, however, may be insufficient to kill *Pseudobalsamia microspora* (truffle), *Chaetomium olivaceum* (olive-green mold), and *Myriococcum praecox* (brown plaster mold) which are more resistant to heating.

Henrici (1930) mentioned the importance of moist heat as against dry heat in the destruction of molds. He stated that spores of *Monilia sitophila*, if wet, are killed in 5 minutes at 72° C., but if dry they require a 30-minute heating at 120° C. As the spores are not easily wetted, they may survive the baking process within a loaf of bread dough, where the temperature may not attain 100° C. Thom and Ayers (1916) also showed that in order to kill some molds dry heat must be twice as high as moist heat. Watanabe (1933) showed that whereas dry air aids in destroying mycelium of fungi, it hinders the destruction of resting organs such as sclerotia of Rhizoctonia.

Murphy and M'Kay (1926) showed that the perennial mycelium of *Peronospora destructor* in onion bulbs can be killed by heating the onions to 43° C. for a period of eight hours. Ramsbottom (1918) found that the eelworm *Ditylenchus dipsaci* (*Tylenchus dipsaci*) is destroyed by immersion of affected narcissus bulbs in water at 43.5° C. for two to four hours.

It is therefore the exception, rather than the rule, for fungus, nematode, and bacterial protoplasm to withstand temperatures between 60° and 65° C., even for a few minutes, under moist conditions. Since insect life also cannot withstand such temperatures and many of the most common plant viruses are destroyed in this range[7], and since most weed seeds are believed to be killed below these temperatures, the author chose 65° C. as the mini-

[7]Exceptions are some which occur in tobacco and tomato.

mum end-point soil temperature to be sought in the experiments described in the following pages.

EXPERIMENTS WITH INDIRECT-SOIL-PASTEURIZING DEVICES

ATTEMPTS TO USE AN ORDINARY SOIL-HEATING CABLE

Even the most successful electric soil pasteurizers thus far designed have the objectionable feature of requiring the soil to be handled once when it is put into the device, and again when it is removed to its permanent site. This situation has led to a search for ways of treating soil in benches and ground beds, without the labor of moving it.

FIGURE 7. EFFECT OF HIGH TEMPERATURE ON LEAD-COVERED SOIL-HEATING CABLE

Left, normal condition of cable. Right, condition after a few hours of use in soil as a pasteurizing device, showing melted lead and injured insulation

A number of unsuccessful attempts have been made to pasteurize with a standard brand of lead-covered soil-heating cable, but this was not suited to withstand the high temperatures needed for this kind of work. What happens to such a cable when used in this way is illustrated in figure 7. In order to avoid melting of the lead sheath, it was necessary to use excessive quantities of the cable per unit volume of soil to obtain the necessary wattage required per cubic foot. The need for a cable that can be used for the dual purpose of soil-heating and -pasteurizing in coldframes, hotbeds, and cutting beds, has often been expressed by both growers and research men.

THE INDUCTION TYPE OF ELECTRIC GRID

One ingenious device for pasteurizing soil in ground beds makes use of the induction principle long employed in certain kinds of electric furnaces and in all transformers. It is essentially a set of iron pipes connected to form a grid somewhat resembling a short wide ladder. A few turns of insulated copper wire are drawn through certain members of the grid, and when alternating current is passed through these coils circulating currents are induced in the iron pipes surrounding them just as in the secondary windings of a transformer. Because of the resistance of the iron pipes, a considerable degree of heat is generated in them.

Two such units have been made by engineers of the Rochester Gas & Electric Corporation, of Rochester, New York, and have been used successfully for a short time in greenhouse soil pasteurization. Since the insulation on the primary wires is subject to high temperatures and a considerable amount of moisture when buried in the soil, it must be carefully selected if durable units are to be obtained. Certain construction difficulties also are met with in assembling this device, but these probably are not insurmountable.

A table giving some of the characteristics of these grid heaters has been prepared by H. A. Brown, of the Rochester Gas & Electric Corporation, and is presented here with Mr. Brown's permission (table 2). The design "A" called for a grid 40 inches long, with eight cross members 6 inches apart and having a heat flux of a little more than 2.5 watts per square inch of pipe surface, the pipe size to be 1 inch. The design "B" was to be 10 feet long, and was to contain only six cross members but with the same heat flux. The heaters were to be used on 115-volt alternating current, and would treat, when buried in the ground, approximately 14 and 30 square feet of bed space, respectively. From the table it is seen that the design chosen for the shorter grid, "A_5", called for 11 turns of no. 12 black waterproofed asbestos-covered copper wire in each of the four loops of the grid, and would have a connected load of 4.2 kilowatts and 41 amperes. The design chosen for the longer grid, "B_6", called for 5 turns of no. 12 wire of the same description in each of the three loops, and would have a load of about 8.4 kilowatts and 79 amperes.

The cost of construction of such grids was rather high, owing to the many threaded elbows. Estimates for materials alone have been placed at approximately $25 for each grid, and the labor is a large item. At present, therefore, further development of the induction type of portable soil pasteurizer does not seem very promising.

TABLE 2. SOME CHARACTERISTICS OF AN INDUCTION HEATING TYPE OF SOIL-PASTEURIZING GRID MADE OF 1-INCH IRON PIPE FOR 60-CYCLE ALTERNATING CURRENT*

Pipe arrangement†	Copper-wire B. & S. gauge	Number of turns	Current in circuit (amperes)	Copper loss (watts)	Iron loss (watts)	Total loss (watts)	Watts per square inch of pipe surface	Voltage on line
A_1.....	22	4	40	664	3,208	3,872	2.50	97.1
A_2.....	14	10	40	1,236	2,636	3,872	2.50	106.0
A_3.....	12	12	40	952	3,872	4,824	3.12	136.0
A_4.....	12	12	33.9	684	2,776	3,460	2.23	115.0
A_5‡.....	**12**	**11**	**41.1**	**916**	**3,264**	**4,180**	**2.70**	**115.0**
A_6.....	10	11	43.7	656	3,700	4,356	2.81	115.0
A_7.....	10	12	37.2	520	3,180	3,700	2.39	115.0
A_8.....	14	11	36.4	1,148	2,656	3,804	2.46	115.0
B_1.....	6	5	102.8	1,323	8,979	10,302	3.27	115.0
B_2.....	6	6	74.8	828	6,507	7,335	2.33	115.0
B_3.....	8	5	98.1	1,917	7,896	9,813	3.12	115.0
B_4.....	8	6	73.2	1,281	5,976	7,257	2.31	115.0
B_5.....	10	5	92.9	2,733	6,834	9,567	3.04	115.0
B_6‡.....	**12**	**5**	**78.7**	**3,120**	**5,256**	**8,376**	**2.66**	**115.0**

*Prepared by H. A. Brown, of the Rochester Gas & Electric Corporation, Rochester, New York.
†Pipe arrangement: A =4 loops 40 inches long spaced 6 inches connected in series.
B =3 loops 10 feet long spaced 6 inches connected in series.
‡Design chosen for experimental models.

BURIED ELECTRIC PIPE-TYPE HEATERS

In the interests of safety and economy, buried pipe-type heaters were tested in benches and ground beds as a substitute for vertical plates and the direct-heating methods already tested by some other investigators—as Dix and Rauterberg (1933), Krewatch and Kable (1933), and Fee (1933). With such heaters, many of the objections to the direct method are eliminated at the start. No transformer is necessary. There are no leakage to the ground, no danger to the operator, and no troublesome contact difficulties between electrode and soil. The demand can be accurately determined before starting, and it does not fluctuate from one test run to another.

Tests in greenhouse bench soil

A series of six pipe-type heaters (Hynes & Cox), of ¾-inch galvanized pipe 40 inches long, each heater rated at 400 watts on 230-volt alternating current, was set up in a bench as illustrated in figure 8. The heaters were spaced 7 inches apart, 3½ and 2¼ inches from the top and the bottom of the bench respectively, which empirical setting proved to be satisfactory. By way of comparison with similar heaters already on the market, a set of two General Electric Calrod soil-sterilizing units was placed in another compartment of the bench beside the first. These Calrod heaters had a combined rating of 1500 watts, while that of the six pipe-type Hynes & Cox heaters totaled 2400 watts. Each of the two bench compartments was 5¾ inches deep and contained approximately 5½ cubic feet of soil, thus giving a wattage per cubic foot of 273 and 436, respectively, in the two compartments. The current employed was 230-volt alternating current.

Seven test runs were completed with this equipment, the object being to determine the current consumed by each unit in raising all parts of the soil from room temperature to at least 60° C. Temperatures were meas-

ured by a set of 20 thermometers placed carefully and read at regular intervals. Three kinds of soil were employed—sand, loam, and muck. The results are summarized in table 3. It is seen that the efficiency of the

TABLE 3. SUMMARY OF TEST DATA ON ELECTRICITY CONSUMPTION WITH TWO KINDS OF HEATERS IN BENCH SOIL OF THREE TYPES

Type of soil	Mean temperature rise in three hours (centigrade)		Mean watt-hours per degree rise per cubic foot of soil		Mean kilowatt-hours per 50 degrees rise per cubic foot of soil	
	Hynes & Cox	General Electric	Hynes & Cox	General Electric	Hynes & Cox	General Electric
Sand	59°	40°	22		1.121	
Sand	57°	38°		21		1.068
Loam	52°	39°	27		1.349	
Loam	64°*	39°*		35†		1.759†
Muck	37°	34°	34		1.711	
Muck	51°*	38°*		28		1.417
Muck	37°*	35°*	32		1.612	
Mean	51.0°	37.1	28.8	28.0	1.448	1.411

*Four-hour instead of three-hour periods.
†It is believed that excessive soil moisture may have been responsible for this rather high figure.

two kinds of heaters was not significantly different. The time requirements were in proportion to their current rating, the higher-rating outfit carrying the soil up to a proportionately higher mean temperature in the same number of hours. Sand was the most economically treated of the three kinds of soil.

A feature of the equipment which was of value in keeping the heat loss down to a minimum, was a 1-inch layer of composition insulating board laid on top of the soil while the heating was in progress (figure 8).

It is thus possible to equip shallow benches with electric heating devices that will adequately and safely pasteurize all kinds of soil on 230-volt current with consumption of approximately 1.5 kilowatt-hours per cubic foot of soil. Considerable variation in the wattage per cubic foot of soil is shown by these tests to be quite permissible if the soil is kept covered. It is admitted, however, that at present the expense of the equipment and the time consumed in handling it do not recommend it as a method of practical value. The equipment for these tests costs approximately $25, and in each case it pasteurized but 5 or 6 cubic feet of soil in three to four hours time.

Some time after the completion of these experiments, a small portable soil sterilizer, employing one 750-watt Calrod unit like the one referred to above, was placed on the market. It is shaped and may be carried like a large suitcase, holds a little more than 2 bushels of soil, operates on 115-volt alternating current, and will pasteurize a charge of soil in four to five hours. The one illustrated in figure 9 has been in use at the entomology greenhouses of Cornell University for several months.

Tests in greenhouse ground beds

To determine the time and the current required to pasteurize soil in a ground bed 10 to 12 inches deep with the above-described portable pipe-type heaters, a set of six, each 40 inches long and of 400-watt rating, was

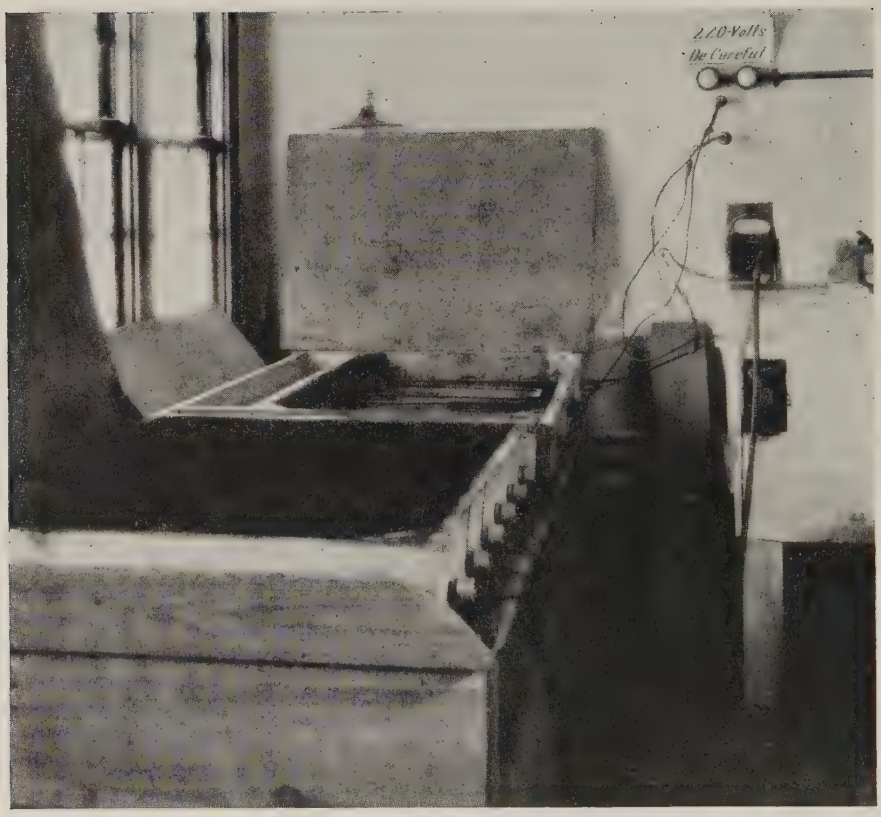


FIGURE 8. A COMPARISON OF TWO KINDS OF SPACE HEATERS IN BENCH SOIL 5¾ INCHES DEEP

The composition insulating board at side and rear is used for covering the soil

buried, the heaters being placed in parallel rows, 7 inches deep and 7 to 8 inches apart. In order to avoid danger of short circuits, watertight right-angled conduit fittings, with short nipples through which the connecting wires could be led above ground, were attached to the ends of each heater (figure 10).

The test plot measured 46 inches wide by 18 feet long, and was heavily infested with *Phytophthora parasitica*. Six changes of position of the heaters, allowing a 3-inch overlap, were sufficient to treat the bed. A period of six to eight hours was required to bring all parts of the soil mass occupied by the heaters up to a minimum pasteurizing temperature to a depth of 11 inches. The total current consumed in thus pasteurizing 10 cubic feet of soil was from 12.2 to nearly 20 kilowatt-hours, depending upon the moisture content of the soil which was purposely altered at times. The results are summarized in table 4. It is seen that as the moisture was increased from 18.8 to 24.7 per cent, the current consumption went up from 26.9 to 44.2 watts per degree rise per cubic foot. Tests made by growing

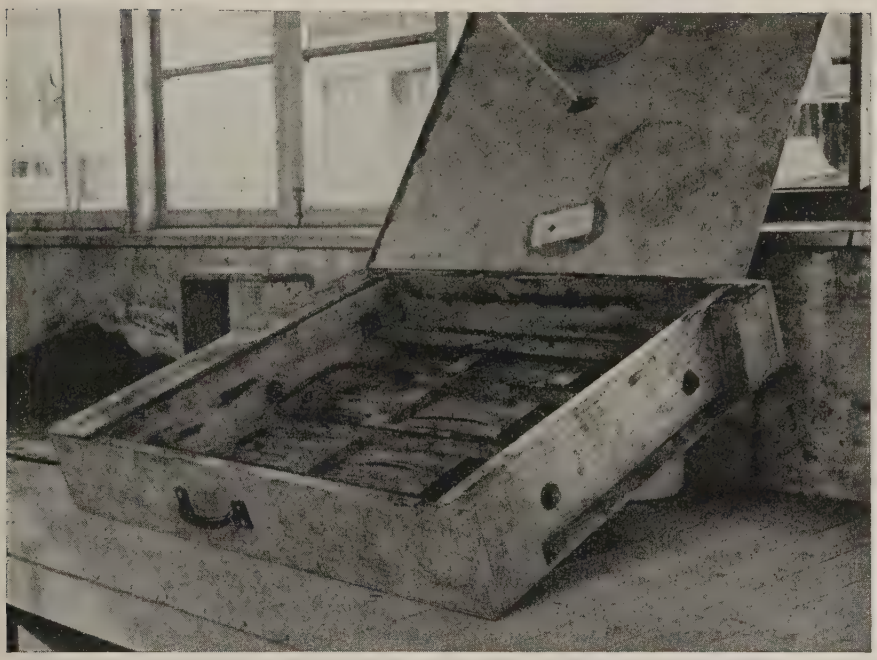


FIGURE 9. A PORTABLE PASTEURIZER FOR 115-VOLT ALTERNATING CURRENT, HOLDING BETWEEN 2 AND 3 BUSHELS OF SOIL. COMPARE WITH FIGURE 8

tobacco plants in treated and in untreated soil indicated that complete control of the Phytophthora disease was obtained by the treatment given to this ground bed.

TABLE 4. SUMMARY OF CURRENT USED IN PASTEURIZING A GROUND BED OF LOAM WITH A SET OF SIX PORTABLE PIPE-TYPE SPACE HEATERS BURIED 7 INCHES DEEP

Test run no.	Mean soil moisture (per cent)	Mean watt-hours per degree rise per cubic foot of soil	Mean kilowatt-hours per 50 degrees rise per cubic foot of soil
6	18.0	26.4	1.320
4	18.8	26.9	1.345
3	19.0	28.3	1.415
5	19.4	31.9	1.599
1	21.0	35.0	1.752
2	24.7	44.2	2.209
Mean	20.28	32.08	1.606

A demonstration of the importance of soil moisture was made by moistening one half of one test plot more than the other half, and noting the difference in mean-temperature readings of the soil in both halves at the end of the seven-hour heating period. On one side the moisture was 18.88 per cent at the start, and on the other side it was 22.05 per cent. At the end of the period the mean-temperature rise of the soil in the drier side was 48.6 degrees centigrade while that of the soil in the wetter side was but

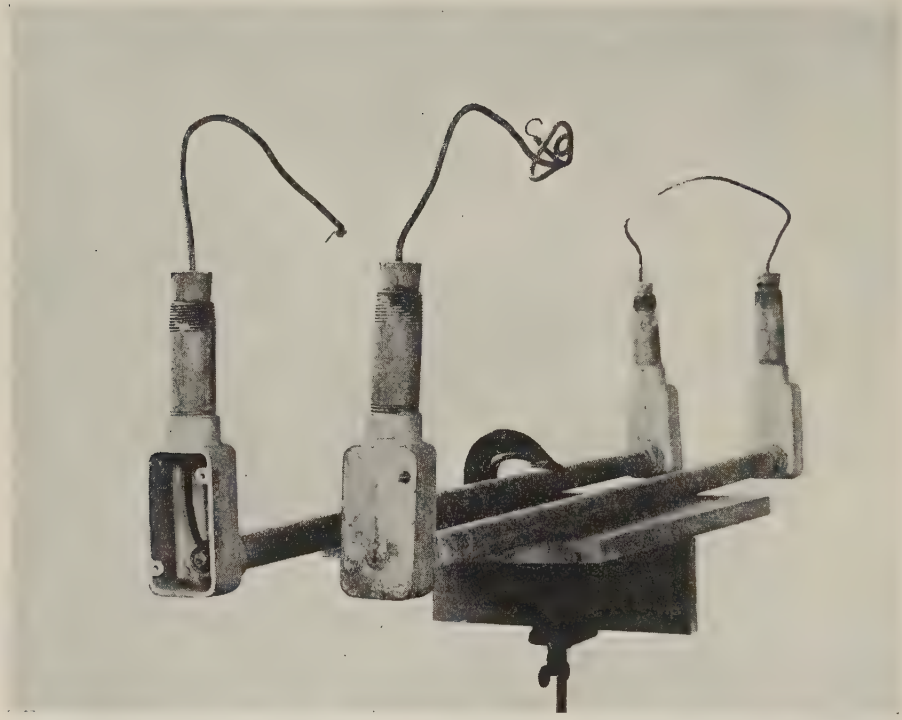


FIGURE 10. A PAIR OF 40-INCH PIPE-TYPE HEATERS, EACH RATING 400 WATTS, SHOWING THE WATERTIGHT CONDUIT FITTINGS AND NIPPLES EMPLOYED ON THE ENDS TO PERMIT SAFE BURIAL AND USE IN MOIST SOIL

42.7 degrees, or 12 per cent lower. In other words, a 14-per-cent-lower initial soil moisture resulted in a 13.8-per-cent-higher mean-temperature rise by the end of the heating period. Similarly, a comparison of test run no. 4 with test run no. 2, in table 4, shows that it required 64 per cent more current to overcome a 31-per-cent difference in initial moisture content of the soil.

TYPES OF ELECTRIC SOIL PASTEURIZERS GENERATING STEAM

Since it appeared that little more could be gained by further experimenting with types of electric heaters that must be buried, dug up, and reset at frequent intervals, attention was turned to the possibility of generating steam with electric heating units close to the soil but not buried in it. That this apparently has not been tried before would seem to be owing to the beliefs (1) that steam must enter the soil under pressure in order to be effective, and (2) that electrical energy is too expensive relatively to other ways of generating steam. Both these ideas evidently need revising.

The author (Newhall, 1930) has reported satisfactory steaming operations, employing the inverted pan, in which good results in eradicating nematodes in ground beds and benches were obtained with steam under less than 12 pounds pressure on the boiler, even when the boiler was 100

feet from the scene of operation. Under such conditions the pressure under the pan itself may be practically nil. Furthermore, on theoretical grounds it is obvious that there is little need for much pressure to drive steam into the soil if one considers the process of heat transfer when the steam enters the soil. In contacting a cold surface, as a particle of soil, the steam is chilled to the point of condensing, and so gives up most of its heat to the soil particle. At the same time its own volume is reduced to a very small fraction of what it was formerly (less than 1/1500). This great reduction in volume enables the steam to pass through the soil, condensing as it passes and releasing its heat, without filling and clogging the open spaces between the soil particles. It therefore takes an almost negligible pressure to drive steam into loose soil which is not already soaking wet.

The importance of having the soil loose, as pointed out by the author (Newhall, 1927), needs no further comment; but the importance of not having it wet can be better understood when one remembers that the specific heat of soil on a weight basis is only from 0.19 to 0.26 that of water, or from 0.44 to 0.57 on a volume basis according to Bouyoucos (1913). A pound of excess water therefore requires 4 or 5 times as many heat units as does a pound of soil, to elevate it to pasteurizing temperatures. Soil should not be too dry (powdery), however, since conduction of heat from one particle to the next can take place better through a thin film of moisture than through a dry air space. With ordinary soil the best results may be expected when the soil barely retains its shape after being squeezed firmly in the hand, rather than crumbling to pieces easily.

The Nixon dairy-utensil sterilizer

The first apparatus tested which employs this principle of steam-heating under atmospheric pressure was designed by M. W. Nixon, of Ithaca, for sterilizing dairy utensils. It has been briefly described by the author (Newhall, 1939, a and b). The steam is generated by a 1500-watt electric hot-plate built into the base of a tight, well-insulated cabinet having one large door in front (figure 11)[8]. The inside measurements in the experimental model employed are; height, 29 inches; width, 28 inches; depth, 15 inches. In the center of the bottom over the hot-plate, and as an integral part of the latter, is a metal pan holding 5 quarts of water which can be brought to a boil in 30 minutes. The device is rated for a 230-volt alternating current. The pan and the heating element are thoroughly insulated with rock wool; and a heat fuse and a time switch are connected in series with the heater, the former to melt in case the water should boil away before the time switch has opened the circuit. Some readers may recognize the similarity between this device and the old Arnold laboratory sterilizer familiar in bacteriology laboratories.

The soil is placed in flats, or trays, piled one above another in the cabinet —which, though having a total capacity of 7 cubic feet, actually holds a net total of only 2½ cubic feet of soil when the soil is in flats 3 inches deep with ¾ inch between the flats. The current is usually left on for nearly two and one-half hours, during which time approximately 3 quarts of water is boiled away and a soil temperature of 60° to 70° C. (140° to 158° F.) is attained. The soil-moisture content is increased by less than 10 per

[8]Now manufactured by the Victor Dairy Products Company, of Hagerstown, Maryland.

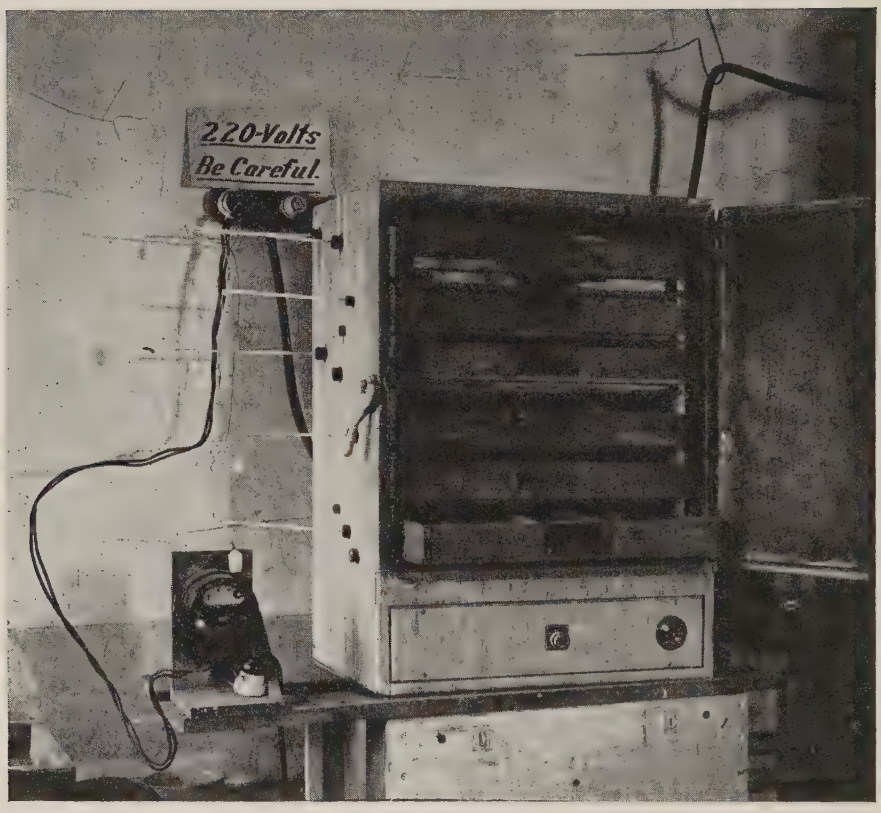


FIGURE 11. THE NIXON ELECTRIC DAIRY-UTENSIL STERILIZER, EXPERIMENTAL MODEL, USED IN MORE THAN 250 TEST RUNS WITH SOIL OF DIFFERENT KINDS, MOISTURE CONTENTS, DEPTHS, AND ARRANGEMENTS

The photograph shows the heat fuse and the time switch in the baseboard

cent, and is practically negligible if the flats are removed while still hot, since they lose much of their moisture while cooling.

In order to determine the conditions under which maximum efficiency could be obtained with this type of pasteurizer, a number of factors were studied in a series of more than 250 test runs[9]. A typical time-temperature curve for a nine-hour period during which the current was on for the first two and one-half hours (figure 12), shows the lag between soil and air temperature, the normal rise in soil temperature of several degrees after the current has been cut off, and the slow cooling reminiscent of the behavior of fireless cookers. As a rule, when the air temperature in the upper corner of the cabinet reached 80° to 85° C., the soil temperature was close to 60° and would advance up to 65° in the next half-hour on the latent heat stored in the heating elements. At the end of this period the soil could be removed, and it could be used as soon as it was cool enough.

[9]Acknowledgment is made of the valuable assistance given by Herbert Roth in collecting much of the data used here.

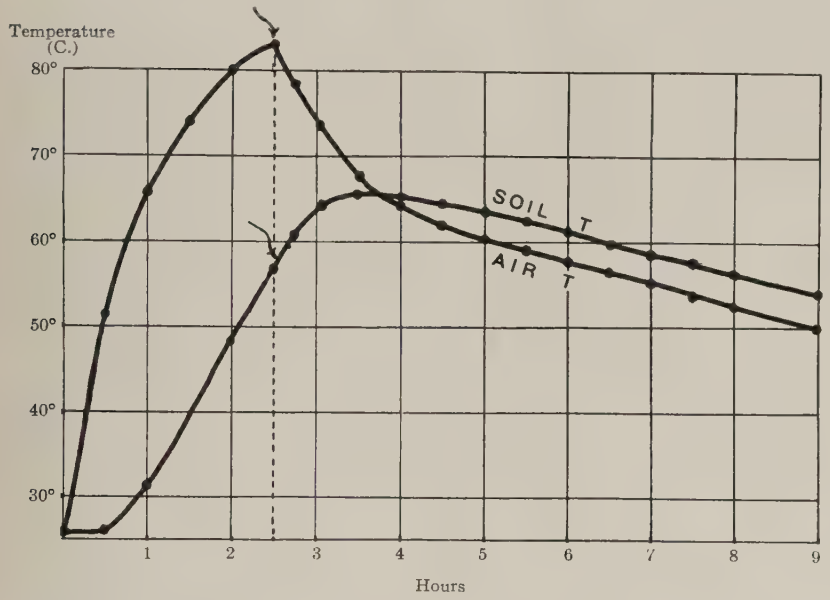


FIGURE 12. A TYPICAL TIME-TEMPERATURE CURVE OBTAINED WITH THE NIXON PASTEURIZER OVER A NINE-HOUR PERIOD WITH THE CURRENT ON FOR THE FIRST TWO AND ONE-HALF HOURS

The relation of the air temperature to the soil temperature, the rise of the soil temperature during the hour following disconnection of the current, and the slow cooling rate of the soil are evident in the graph

The role of initial soil moisture

A comparison of the time-temperature curves of two samples of loam soil, with initial moistures of 9.4 per cent and 21.3 per cent, respectively, will serve to illustrate the importance of soil moisture in determining the current consumed and the time needed to reach a given temperature with loam soil. Such a comparison is shown in figure 13. It required nearly an hour longer to heat the wetter soil up to 65° than to heat the drier soil to that temperature.

Effect of varying the soil depth

The question whether the same volume of soil, in this case 2½ cubic feet, can be heated more economically if spread out in a number of comparatively thin layers rather than in fewer but deeper layers, was answered in the affirmative by tests the results of which are summarized in figure 14. The deeper the flats of soil, the longer is the heating period required to reach any given temperature. For example, soil 3¾ inches deep reached 65° C. in one and three-quarter hours of heating, while soil 5½ inches deep reached only 54°, and soil 9½ inches deep reached only 43°, in the same length of time. Muck soil, with its higher moisture content, was particularly affected by this depth factor.

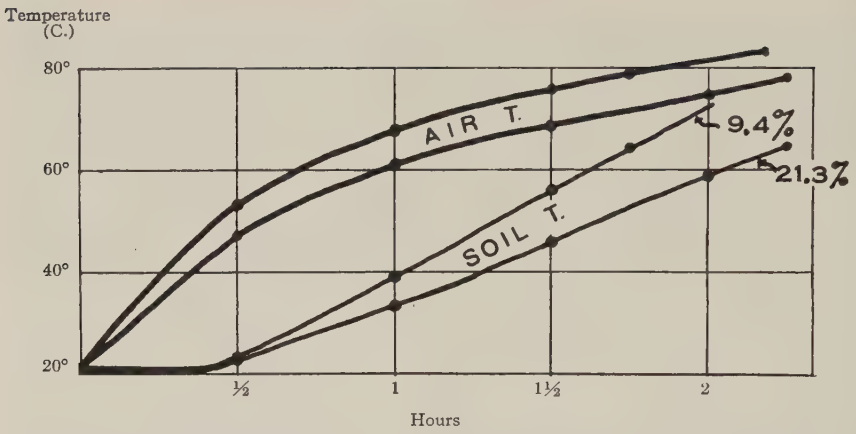


FIGURE 13. EFFECT OF TWO DIFFERENT INITIAL SOIL MOISTURES ON THE TIME REQUIRED TO ELEVATE SOIL TO 65° C. IN THE NIXON PASTEURIZER, AND ON THE RELATIONS OF THE AIR TEMPERATURE IN THE CABINET TO THE SOIL TEMPERATURE

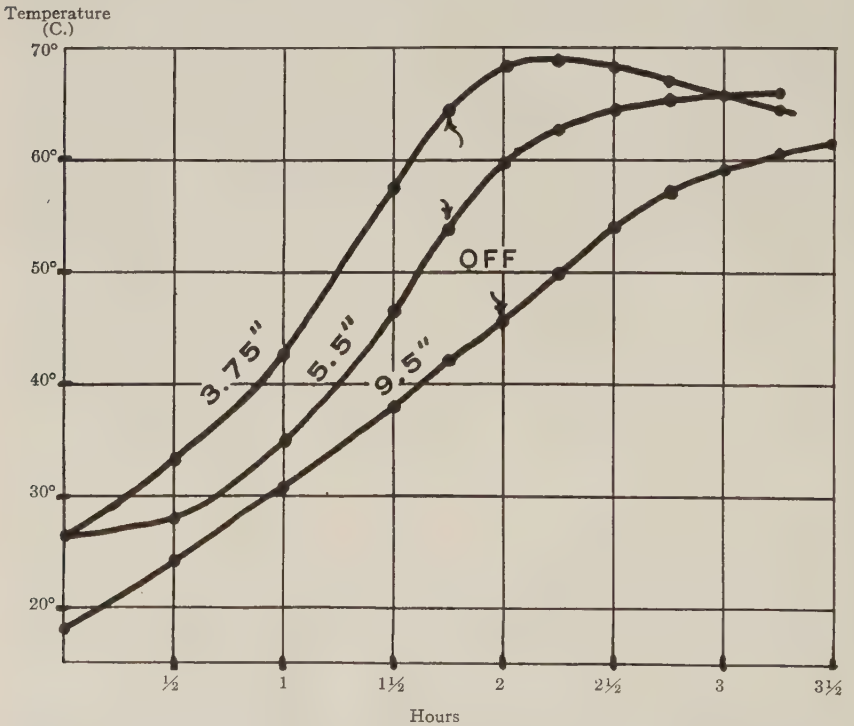


FIGURE 14. EFFECT OF THREE DIFFERENT SOIL DEPTHS ON THE TIME REQUIRED TO RAISE THE TEMPERATURE OF 2½ CUBIC FEET OF LOAM SOIL TO 65° C. IN THE NIXON PASTEURIZER

The current was on during the first one and three-quarters to two hours

Effect of varying the soil volume

Another factor that has a bearing on the general efficiency of the pasteurizer in question, is the ratio of soil volume to size of the heating element. No attempt was made to try different-sized heating elements; but by varying the volume of the soil and keeping records of the current consumed per cubic foot of soil per 50° C. rise in temperature, there was found to be a relation between volume and current consumption, indicating that greater efficiency was obtained when the cabinet was filled to capacity (2½ cubic feet) than when it was only half filled. The latent heat-absorbing capacity of the heater itself has a bearing on this. The time required to attain a given temperature was almost directly proportional to the volume of soil being heated. Both these relationships are summarized in figure 15. There is some indication from this that the 1500-watt heater employed could be used in a cabinet of still larger size than this one.

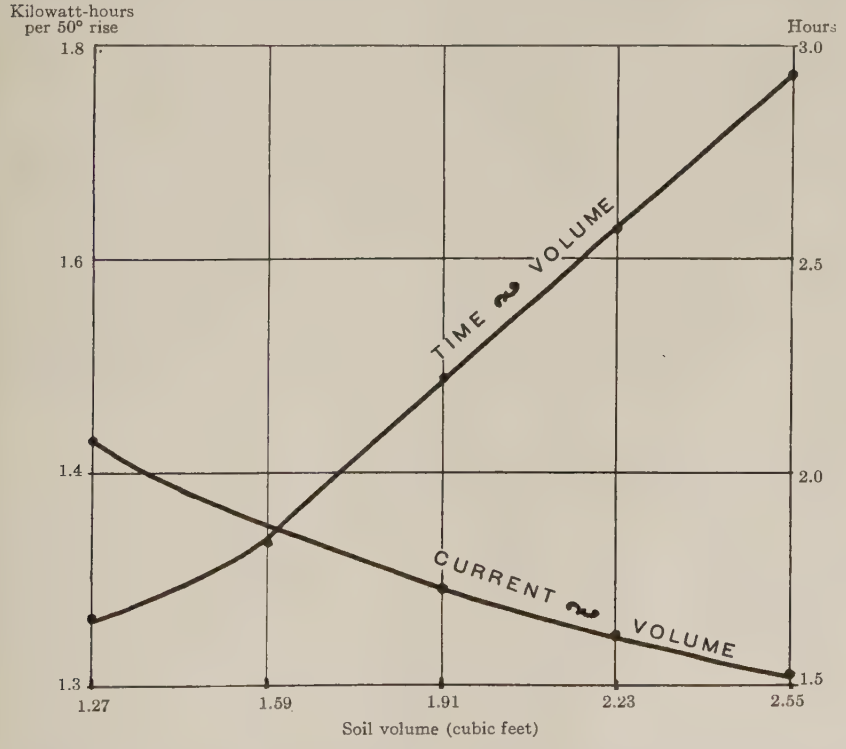


FIGURE 15. EFFECT OF INCREASING THE VOLUME OF SOIL TREATED, ON THE TIME REQUIRED FOR THE SOIL TO REACH 65° C. AND ON THE CURRENT REQUIRED PER CUBIC FOOT OF SOIL

Effect of other miscellaneous factors

Mention has already been made of the latent, or stored, heat in the heaters that could be relied on to raise the soil temperature another 5 to 8 degrees in less than an hour after the current has been turned off. It

must be obvious from this, that the greatest efficiency is attained by continuous operation, one charge of soil following another.

A study of efficiency in relation to a loose as compared with a compact condition of the soil in the trays, revealed little difference in the case of sand but a measurable difference with muck. By packing the muck in the trays a considerably larger amount could be put in, which increased the load by just that much.

Arrangement of the flats in the cabinet with respect to clearance around the edges and between them, was of importance in permitting easy access and free circulation of the steam. A clearance of 1 inch all around is believed to be the most satisfactory. Leaving an open space resembling a chimney up through the center was of little benefit. Greater efficiency was obtained when that space was filled with soil.

Alternate periods of heating, in which the current was turned on for 10 minutes at a time and off for 10 minutes, only seemed to increase the time required for the soil to reach 65° C., without decreasing the current consumption.

The temperature of the water at the start was of less importance than might be supposed at first thought. Very little was gained in efficiency by starting with hot water (82° C.) as against water at room temperature. The reason is apparent from a consideration of the following facts. The heat required to raise 1 pound of water through 1 degree Fahrenheit is, by definition, 1 B.T.U. In 3½ quarts there are 7.3 pounds, so that 1036 B.T.U. are required to raise that amount of water from room temperature (21° C.) to the boiling point (100° C.). But to convert 7.3 pounds of water to steam after it has reached the boiling point requires another 970.4 B.T.U.×7.3, or 7084 B.T.U. From this it is evident that heating the water up to the boiling point takes only about one-seventh of the total energy consumed in the entire operation. Incidentally, this also shows why a pound of water converted into steam is so much more effective than a pound of boiling hot water, in treating soils.

Mean current consumed per cubic foot of soil

Summarizing 150 of the test runs made with the Nixon pasteurizer, the current required to raise 1 cubic foot of soil to a temperature of 65° C. from an original temperature of 15° was found to lie between 1.15 and 1.68 kilowatt-hours for sand (mean 1.34, or 27 watts per degree), between 1.16 and 1.62 kilowatt-hours for loam (mean 1.39, or 28 watts per degree), and between 1.54 and 2.05 kilowatt-hours for muck, with its higher moisture content (mean 1.78, or 35 watts per degree). The variations observed between tests of any one kind of soil are due largely to variable soil-moisture content, soil depth, degree of soil compactness, and initial temperature of the heater. There is no significant difference in requirements between sand and loam, but the greater current consumption of muck as compared with the other two kinds of soil is highly significant statistically and is believed to be due to the greater proportion of water in the muck.

Some considerations relative to specifications for a larger model

In considering the construction of a larger pasteurizer capable of treating twenty-five flats at a time instead of six, a question arises as to how tall such a pasteurizer could safely be built without sacrificing efficiency.

While no tests were run, the impression was gained that disappointing results might be obtained if the pasteurizer were much more than 3 or 4 feet high, as there might be too great a difference in temperature between the top and the bottom flat at any given time. These variations were usually of only a few minutes duration in the cabinet under test, but, as they sometimes amounted to 10 or 15 degrees centigrade, they suggest that it might be better to enlarge in a horizontal rather than in a vertical plane.

A larger cabinet, capable of holding twenty-five flats 12 by 24 by 3½ inches in size, or nearly 15 cubic feet of soil (net), would require six 1500-watt heaters with a connected load of 9 kilowatts on 230 volts, or approximately 50 amperes. This is based on a rating of 600 watts per cubic foot of soil. To allow for circulation and space to be taken by the flats themselves would require a volume close to 45 cubic feet, which could be supplied by a cabinet with inside dimensions as follows: height, 30 inches; width, 7 feet 8 inches; depth, 28 inches. A lower wattage rating per cubic foot may be adequate.

The Cornell electric inverted steam pan

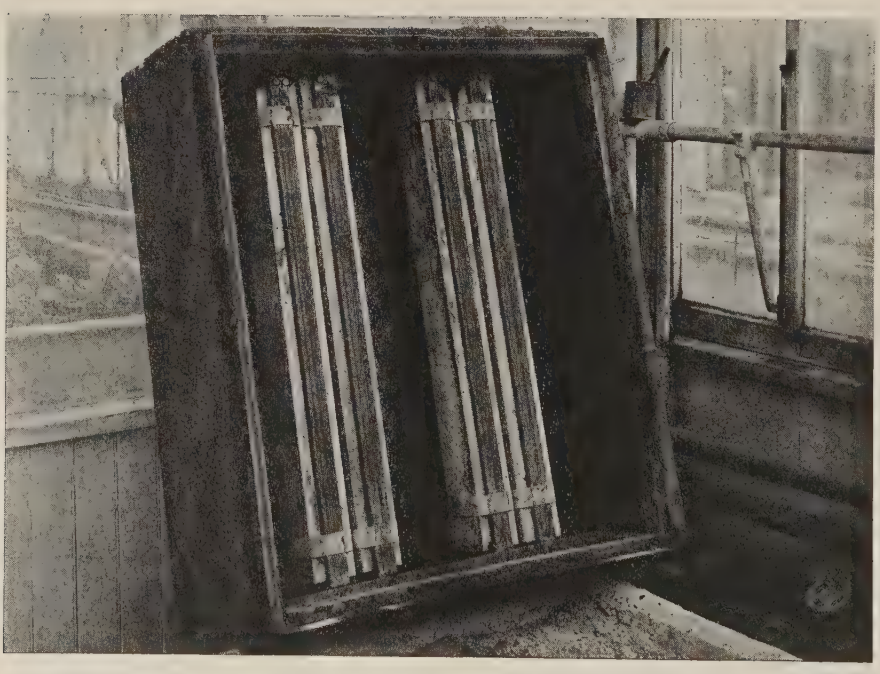
The success obtained with the Nixon dairy-utensil sterilizer as a soil pasteurizer prompted the construction of a portable device, briefly described by the author in an earlier publication (Newhall, 1939b), for use on greenhouse benches, ground beds, coldframes, hotbeds, and cutting beds. This is essentially an inverted pan similar to those long in use by greenhouse growers. But instead of steam being piped to it from a distant boiler, a 230-volt alternating current is brought to the pan and the steam is generated beneath in troughs of water heated by strap heaters (figure 16).

The experimental model was made of 1-inch insulating board over a light wooden frame. Its dimensions were 2½ feet wide by 3 feet long by 1 foot high. A 2-inch strip of galvanized iron around the lower edges helped to seal the edges when the pan was pushed down on the soil. The four metal water reservoirs inside held approximately 5 quarts of water each, and they were filled through stoppered holes in the top. The four 1500-watt heaters were wired in parallel; so that a constant demand of 6 kilowatts was employed to steam 7½ square feet of soil, which was accomplished to a depth of approximately 10 inches in two to three hours.

Tests were made in ground beds of loam soil with moisture contents ranging from 11 to 15 per cent. To facilitate accurate measurement and to gain a more complete picture of the rise in temperature of the soil at different depths and locations beneath the pan, thermocouples of copper constantan were buried at 3-, 6-, 9-, and 12-inch depths. One set was placed 3 inches in from one corner, another near the middle of one side, and a third under the center of the pan. The soil was loosened with a spading fork before the pan was placed over it. A graphic presentation of the temperatures obtained at the different levels is shown in figure 17.

It took 20 minutes to start the water boiling. The soil temperature began rising at the 3-inch depth 10 or 20 minutes later. In 60 minutes it began to rise at the 6-inch depth, and in 90 minutes at the 9-inch depth. The current was turned off in two hours, at which time the temperature was rising at the 12-inch depth. At the lower levels the temperature continued to rise for some time at a rate similar to the rate of fall in the

A



B

FIGURE 16. THE CORNELL ELECTRIC INVERTED STEAM PAN

A, In use on a raised ground bed
B, Tipped on end, showing the arrangement of the four 1500-watt strap heaters beneath the water reservoirs. (See figure 19)

upper layers. Maximum temperatures at the lower depths in the corner were 20 degrees centigrade lower than those under the center of the pan. The water continued to boil for about 15 minutes after the current was turned off, and, as the pan was not moved, there was undoubtedly a con-

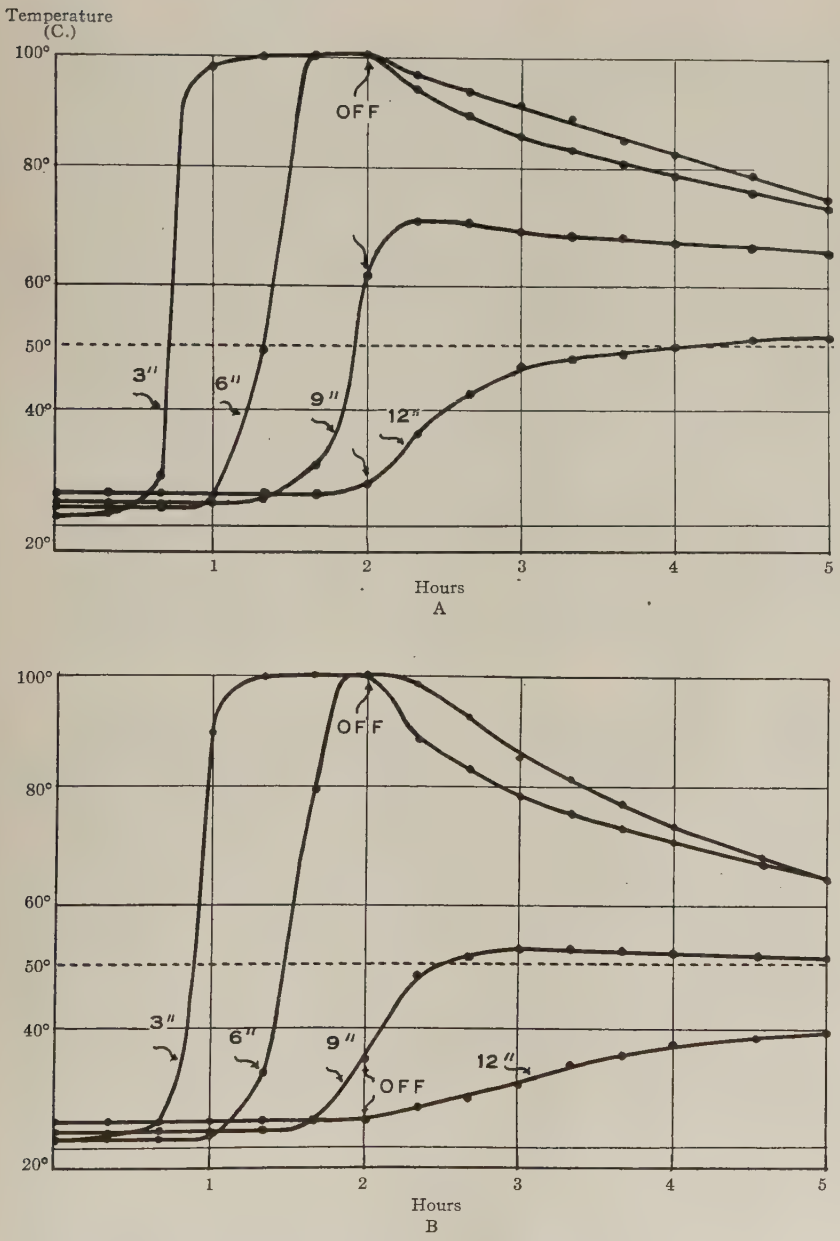


FIGURE 17. SOIL TEMPERATURES ATTAINED IN A GROUND BED OF LOAM AT 3-, 6-, 9-, AND 12-INCH DEPTHS BENEATH THE CORNELL ELECTRIC INVERTED STEAM PAN DURING A TYPICAL TEST RUN

A, Temperatures at points under the center of the pan
B, Temperatures at points 3 inches in from one corner
The current was on during the first two hours

siderable amount of stored heat given off from the heaters during the next three hours. In practice the best results were obtained by laying a piece of 1-inch composition insulating board on the freshly steamed soil to conserve the heat, and by continuous use of the outfit, which called for shifting it to a new position every two hours, never permitting the heaters to cool off.

The current consumed in treating 7½ square feet of soil was metered at 11 kilowatt-hours, or 1.47 kilowatt-hours per square foot. Assuming pasteurization to a 10-inch depth means 1.76 kilowatt-hours per cubic foot of soil, which is similar in efficiency to that with other methods already described.

A test run on loam made with three of the four 1500-watt heaters produced the results shown in figure 18. It is evident from this figure that

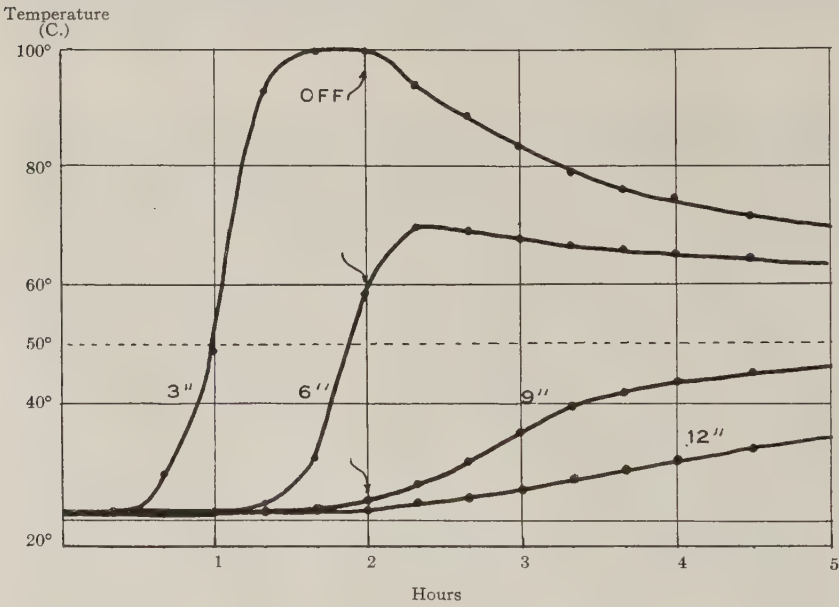


FIGURE 18. SOIL TEMPERATURES ATTAINED IN LOAM AT 3-, 6-, 9-, AND 12-INCH DEPTHS BENEATH THE CORNELL ELECTRIC INVERTED STEAM PAN WHEN OPERATING ON THREE OF THE FOUR 1500-WATT HEATERS

(To be compared with figure 17, A)

pasteurizing temperatures could not be expected much below the 6-inch level without increasing the time of operation beyond two hours. This could be done, however, as there was always some water left in the reservoirs at the end of the two-hour heating period.

From these tests it was deduced that the four heaters used would be adequate for a pan of 25 or 30 per cent larger area, or approximately 10 square feet, without increasing the required heating period too much. Accordingly such a pan was built of asbestos board and angle iron by the Joseph Harris Seed Company, and was put into operation on that company's slat-house soil out-of-doors in the spring of 1939 (figure 19).

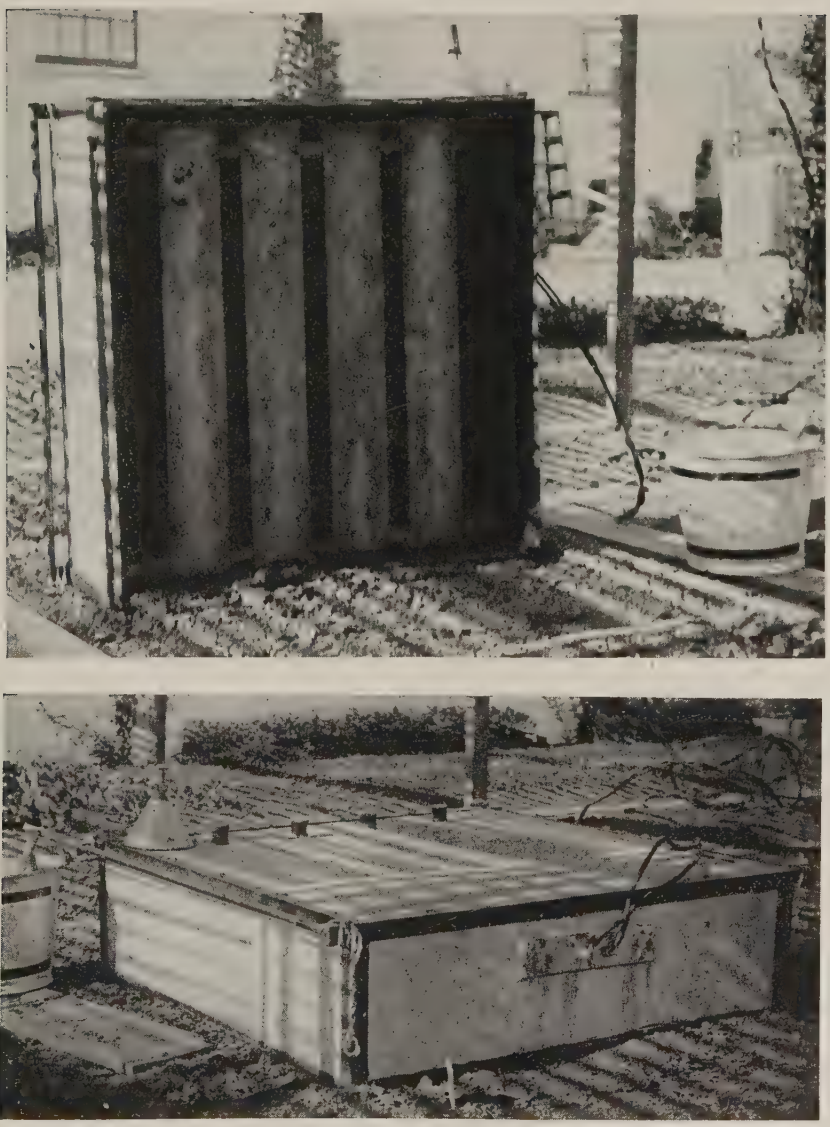


FIGURE 19. MODEL OF AN ELECTRIC SOIL PASTEURIZER BUILT OF ASBESTOS BOARD AND ANGLE IRON, COVERING 10 SQUARE FEET OF SOIL

This pasteurizer, used outdoors on slat-house soil of the Joseph Harris Seed Company at Coldwater, New York, is heated by four 1500-watt strap heaters. The upper photograph shows the strips of asbestos board which shield the soil from direct radiation

Periods of operation of 45 minutes were sufficient to reduce the number of weeds (chiefly grass) from nearly 500 per square yard to less than 12, which amply paid for the current consumed. Such treatment also seemed to eliminate all damping-off of delphinium, which is very subject to this

trouble. Temperatures up to 65° C. were attained 4 or 5 inches below the surface of the soil.

Limitations, advantages, and suggested improvements

At this point it is easy to see that limitations as to the area which can be steamed with electrical energy are imposed by the limited size of the service lines at most men's disposal. To provide for an area of 150 square feet at a time, which is not large in commercial operations employing steam, would require a battery of sixty 1500-watt heaters, which would demand 90 kilowatts, or more than 400 amperes. This load would require a transformer, conduits, and heavy cable, and would increase considerably the difficulties and hazards in manipulating the apparatus. All electrical methods for the average grower are definitely limited to comparatively small operations where large areas do not have to be treated in a few days' time.

One advantage possessed by the electric inverted pan is the fact that the surface of the soil is left in a comparatively dry condition, owing to the radiant heat given off by the strap heaters just above the soil. For some situations this is an improvement over methods which may leave the soil in a puddled condition. However, there was evidence that this too can be overdone to the point of overheating the surface soil. In order to avoid such overheating, strips of Transite,[10] 4 inches wide and ½ inch thick, were mounted immediately beneath the strap heaters. These reduced the direct radiation from the heaters to the surface of the soil.

Longer life could be built into this pan by giving the inside a heavy water-proof coating to prevent the insulating board from absorbing moisture. The pan could be made more rigid by lining or covering it with sheet metal, or by using angle iron on the edges; but care must be taken to guard against short circuits and current leakage in the highly saturated atmosphere within the device. It would be desirable to have some means of determining how much water remained in the reservoirs at any time. Also, a spirit level could well be made a part of the regular equipment.

The Hutchings continuous electric soil pasteurizer

In the spring of 1939 the author was invited to collaborate in designing and testing an ingenious soil pasteurizer made by Donald Hutchings, of the Joseph Harris Seed Company at Coldwater, New York. The device, illustrated in figure 20, is unique in its resemblance to modern electric baking ovens of the continuous type or to some types of flash pasteurizing equipment. The soil, which is dumped into a hopper at one end, begins coming out at the other end in 5 minutes, at a temperature of 65° to 80° C. Its passage through the pasteurizer is regulated so that the organic matter is not overheated and yet a sufficient temperature is attained to kill pathogenic organisms and nearly all weed seeds. A few seeds of legumes survive. The soil is propelled through the pasteurizer by a specially constructed continuous chain operated by a ⅓-hp electric motor. The speed is controlled by a motor on a reducing gear and a set of pulleys of varying sizes. The chain picks up the soil under the hopper and drags it horizontally in small piles, ½ inch deep, across a stainless-steel table 6 inches

[10] A Johns-Manville product containing asbestos.

FIGURE 20. THE HUTCHINGS CONTINUOUS ELECTRIC SOIL PASTEURIZER, IN USE AT COLDWATER, NEW YORK

This device draws 10 kilowatts and pasteurizes 6.6 cubic feet of soil per hour

wide by 64 inches long. This table is heated from below by a number of strap heaters with a total effective wattage of 5.340 kilowatt-hours. Additional heat is directed downward on the moving soil by a set of six 1000-watt "sunbowl" heaters mounted just above and having a total effective wattage, on 205 volts, of 4.625 kilowatt-hours. All of this mechanism is fully enclosed and insulated against heat losses to the outside air. Approximately 15 minutes is required to create a sufficient temperature within the box. After that, 18 to 20 flats of soil can be put through each hour, or 6.6 cubic feet, which means that 1 cubic foot is treated with approximately 1.5 kilowatt-hours after pre-heating of the device, or about 0.5 kilowatt-hour per flat.

As the soil drops into empty flats which are then left overnight in piles, it retains much of its heat for some time and probably exercises some pasteurizing effect on the flats themselves. The temperature of the soil after standing for an hour in the center of one of these piles of flats, was still 50° C.

In testing the device, flats of previously prepared loam known to be infested with damping-off organisms and adjusted to various moisture contents were put through the pasteurizer. Each flat was then planted with 150 seeds of cucumber, which is very subject to damping-off. Nearly perfect stands were obtained in all of the treated flats, while the stands in the two untreated flats averaged only 74 per cent. The temperatures, moisture contents, and stands of cucumbers and weeds in this test are summarized in table 5.

The driest sample of soil (8 per cent) was too dry, since it came out of the pasteurizer in a slightly dusty condition. The wettest sample (56 per

TABLE 5. RESULTS OF TESTS OF THE HUTCHINGS CONTINUOUS ELECTRIC SOIL PASTEURIZER, MARCH 1939

	Original soil moisture (per cent)	Original soil temperature (C.)	Final highest soil temperature attained (C.)	Stand of cucumbers (per cent)	Number of weeds per flat
Untreated soil:					
Check 1	10	20°	20°	68	20
Check 2	10	20°	20°	80	25
Treated soil:					
Dry 1	8	3°	68°	98	0
Medium dry 2	16	5°	69°	99	0
Medium moist 3	23	7°	76°	100	0
Wet 4	56	4°	75°	100	0

cent), on the other hand, was too moist, because it tended to pack between the cross members of the chain which propelled it. Excess moisture has been found to cause some soils to ball up in an unsatisfactory manner. Although vapor can be seen passing off as the soil drops from the end of the pasteurizer, there is very little evident change in total moisture content during the entire process because of the short time that has elapsed, the comparatively low maximum temperatures reached, and the covering of each flat by its successor.

Whether this rapid pasteurizing of soil will prove adequate to control all soil-inhabiting pathogens and all weed seeds remains to be seen. But to obtain higher soil temperatures or longer heating periods simply requires different-sized pulleys to slow up the passage of the soil a little. One important factor in the success of this device may be the prompt piling of treated flats so that the heated soil may cool slowly, like a fireless cooker, for several hours. This practice will probably control even the most difficult organisms. A good many hundreds of flats of soil have been put through this machine during the past two seasons, with very satisfactory results.

Needless to say, the soil must be free from all stones, sticks, or other solid objects which could clog the mechanism, permit overheating, and cause unnecessary delays. It is necessary to employ heaters that will stand the high temperatures resulting from their confinement, and to use plenty of good thermal insulation to avoid heat losses.

DISCUSSION

In the testing of several different types of electric soil-pasteurizing devices, the author has had in mind the ever-increasing demand for a dependable, economical, and safe means of ridding the soil of its parasitic microorganisms, weed seeds, and insect pests. The use of electricity in heating soils is advantageous for several reasons. One is that heat is universally effective against practically all the pests commonly found in soil. Another is that electricity is becoming more available at rates that are increasingly inviting. Still another is that in many places where the climate is too mild to warrant steam-heating equipment, electricity is a logical substitute as a source of power for heat.

Cabinet types of electric pasteurizers have been in use for eight years and have proved successful for potting soil, flats, and benches where some extra handling of the soil was not particularly objectionable. But the

problem of economically treating soil in ground beds, coldframes, hotbeds, and cutting beds without having to cart the soil to and from the pasteurizer, has never been satisfactorily solved for the man who has no available source of steam. While the tests reported herein show that it is possible to use buried pipe-type electric heaters for this purpose, the labor and expense involved will probably hinder the adoption of this method.

The development of the Nixon electric dairy-utensil sterilizer paved the way for successful application of the same principle to a portable inverted steam pan operated by electricity. It is felt that in developing this device some progress has been made toward solving the question of a method of pasteurizing soil in place without having to move it, where only electricity as a source of heat is available. At present the process is not rapid enough to recommend the adoption of the method where large areas must be treated quickly. For example, it took 14 hours to treat 125 square feet of cutting bench with a pan covering 7½ square feet at a time and drawing nearly 6 kilowatts. Although the cost of $1.25 for current (2 cents per kilowatt-hour, or 1 cent per square foot) was low enough, the time consumed was too long to justify recommending the method for large areas. Increasing the size of the pan to hasten the work puts heavy demands on the service line and increases the hazard, so that at present the device is adapted to comparatively small operations. However, the ease with which it pasteurizes loam to a depth of 8 or 10 inches with the expenditure of only 1.5 kilowatt-hours per square foot, and a cost for construction as low as that of most other pasteurizing equipment of like capacity,[11] recommend this pasteurizer for trial not only in greenhouses but also on coldframes, hotbeds, and cutting benches, on outdoor slat-house soil, or wherever an ordinary inverted steam pan could be used. The size employed in these experiments drew slightly less than 30 amperes on a 230-volt alternating-current supply line.

For the firm or the individual employing a considerable amount of soil for seedling flats or pots every day, a pasteurizer of a continuous semi-flash type, which will heat enough soil in a few hours for the next day's needs without changing the moisture content appreciably, may prove useful in regions where electric rates are comparatively low. The Hutchings continuous electric soil pasteurizer built on these lines has been in successful operation for two seasons with an expenditure approximating 1.5 kilowatt-hours per cubic foot, or less than 1 cent per flat. Reduction in the cost of weeding is said to offset this expense. An advantage pertaining to both the Nixon and the Hutchings device, particularly the Hutchings, is their ability to kill plant pathogens without subjecting the soil to a long sterilizing period at unnecessarily high temperatures. It is believed that low-temperature pasteurization and speed are both of importance, especially where soils that are rich in nutrients and high in lime are being heated. Such soils are very likely to be temporarily injured by overheating, which results in poor germination and poor seedling growth.

Injury from overheating rich soils seems to be due in general to the increase in soluble salts, particularly to an increase in nitrates and ammonium salts brought about by reduction of the organic nitrogen as shown by Lyon and Bizzell (1910), Johnson (1919), and other investigators. Not all soils

[11]The chief item of expense was $20 for the four heaters themselves, while other items brought the total cost of materials to approximately $28.

are equally affected, but composts are perhaps the most readily injured. Some plants, such as lettuce, sweet peas, snapdragons, spinach, and tomatoes, are more sentitive to these adverse changes than are others. Plants of the grass family, the cucurbits, and other deep-rooted plants are more resistant. The changes are temporary and are somewhat proportional to the richness (organic content) of the soil as well as to the length of the heating period and the temperature used. After a few weeks of retarded growth, plants in overheated soils usually experience a period of stimulated growth.

Injury from overheating soil can often be remedied by prompt leaching with hot or cold water in amounts up to 3 or 4 gallons to a square foot of soil. Such soil is also benefited by simply postponing its use for 10 to 20 days to permit the resumption of bacterial and fungal activity, or by liberal applications of superphosphate or of organic matter such as chopped straw. Herzog (1939) has recently stated that fungal activity during a 42-day period following soil sterilization is much greater in acid soils (pH 4.7) than in alkaline soils (pH 7.6).

Lawrence (1938) recommends the treatment of loam soil for composts, and of manure or leaf mold, separately, and mixing them afterward. This is especially advised if the compost is not to be used for several months. Loams high in lime are more likely to suffer injury than are acid soils, and lime should not be added to a soil before pasteurizing. If these simple rules are adhered to, the most satisfactory results should be obtained in the growing of seedlings and other plants in soils from which all pathogenic organisms have been eliminated by pasteurization.

SUMMARY

From a consideration of the thermal death-points of more than 120 plant-pathogenic microorganisms, coupled with practical soil tests, the conclusion is reached that a final soil temperature of 65° C. (150° F.) is sufficiently high to ensure pasteurization against all important plant pathogens as well as most weed seeds.

Electrical means of pasteurizing soils divide themselves into two general methods, the direct-heating and the indirect-heating. Since the advantages with respect to safety lie principally with the indirect-heating method, a number of attempts were made to extend the usefulness of this method, which involved the testing of different kinds of equipment.

Experiments with ordinary soil-heating cable showed this to be unable to withstand the temperature required of it in soil-pasteurization work.

An induction type of electric pipe grid was employed more or less successfully for a short time by one of the electric power companies; this is described on page 13.

Soil in greenhouse benches and ground beds was brought up to pasteurizing temperatures with a series of buried portable pipe-type heaters, of ¾-inch galvanized pipe, having a rating of approximately 100 watts per linear foot and spaced to give 220 to 400 watts per cubic foot of soil.

Successful use was made of the new Nixon electric dairy-utensil steamer for pasteurization of soil in flats, or trays. The characteristics of this device were studied in a series of more than 250 test runs, in which it was shown that pasteurizing temperatures could be obtained in two to three

hours at an expenditure of approximately 1.37 kilowatt-hours per cubic foot of soil treated. No appreciable pressure of the steam generated is necessary for adequate soil treatment.

A portable, electrically operated, inverted steam pan was tested. With this device, pasteurizing temperatures in bench and ground-bed soil were obtained to a depth of 7 to 10 inches in two hours with the expenditure of approximately 1.5 kilowatt-hours per square foot of soil. The device appears to have promise as a means of treating coldframe, hotbed, cutting-bench, seedbed, and slat-house soil while in place.

A continuous or semi-flash type of electric soil pasteurizer was tested, in which the soil is placed in a hopper at one end and discharged 5 minutes later from the other end, having attained a temperature of 65° to 80° C. on its way through at an expenditure of 1.5 kilowatt-hours per cubic foot of soil treated.

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